

# The Evolution of Payload Data Capabilities on the Commercial Visiting Vehicles that Service the International Space Station

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For over 10 years, NASA has been working with U.S.-based commercial companies to support the design, development, and operations of new commercial space vehicles. The purpose of these vehicles is to provide cargo and crew transportation services to the International Space Station (ISS) and to stimulate the commercial space transportation industry to Low-Earth Orbit (LEO). Along with the ability to provide a couple tons of cargo to the ISS each mission, the commercial visiting vehicles also provide the ability to transfer NASA payloads to and from the ISS in an active, powered state. To take advantage of this capability, NASA requirements for the data services that payloads need while they are integrated into the visiting vehicles have grown with each set of commercial contracts. Today, NASA desires for payload data services encompass a variety of capabilities including payload health and status (H&S) telemetry monitoring, visiting vehicle environment data monitoring, and payload commanding. The intent of these capabilities is to provide payload developers with situational awareness and the ability to quickly diagnose any problems with payload operations prior to vehicle docking or post-landing to support immediate troubleshooting response. As new requirements for payload data services have emerged over the years, the ISS Payload Operations Integration Center (POIC) at the NASA Marshall Space Flight Center (MSFC) has established ground segment interfaces to the visiting vehicle control centers to enable payload developers to use these services. Many technical and programmatic challenges have been faced while establishing these interfaces. The most significant challenge faced has been in finding the right balance amongst providing interfaces to payloads that are compatible with the ISS so that payload hardware or software changes are not necessary to ensure compatibility with the visiting vehicles; keeping POIC ground system development costs low by standardizing implementation approaches across commercial vehicle partners; and fostering commercialization through supporting vendor-unique implementations that are commercially economical. This paper will first detail the data services that will be available to payload users under each commercial visiting vehicle contract. Secondly, this paper will offer discussion of the most significant technical and programmatic challenges faced to-date in offering these new data services to payload developers.

## I. Introduction

IN 2008, NASA awarded the first contracts to U.S. commercial companies to execute the delivery of cargo and supplies to the International Space Station (ISS). These contracts, called the first phase of Commercial Resupply Services (CRS1), were awarded to Space Exploration Technologies (SpaceX) and Orbital Sciences following a series of earlier contracts that had been awarded to various companies to support vehicle development and demonstration efforts [1]. Under the CRS1 contracts, commercial visiting vehicles not only provide a couple tons of cargo to the ISS

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each mission, but they also provide the ability for NASA payloads to be transferred to and from the ISS in an active, powered state. Prior to the start of commercial cargo resupply missions, most vehicles that serviced the ISS transported science experiments as passive cargo. Therefore, the CRS1 program ushered in a new era in which NASA and payload developers could reimagine payload operational concepts during the transit phase to and from the ISS through offering frequent flight opportunities with powered payload transport capability.

To take advantage of powered payload transport capabilities, NASA first added requirements under the CRS1 program for the commercial vehicles to provide telemetry monitoring services for pressurized payloads to give payload developers situational awareness during the transport phase. Since then, payload developer use-cases for visiting vehicle data services during free-flight have evolved with each new commercial visiting vehicle contract to cover a variety of payload monitoring and control abilities. Additional commercial contracts include the Commercial Crew Transportation Capability (CCtCap) contracts that were awarded to SpaceX and Boeing, and the second phase of Commercial Resupply Services (CRS2) contracts that were awarded to SpaceX, Orbital ATK (formerly Orbital Sciences), and the Sierra Nevada Corporation [2, 3]. Commercial crew flights will commence in 2018, and the first flight under the CRS2 program is currently planned for 2019.

As new requirements have been added on to commercial visiting vehicle contracts for payload data services over the years, the ISS Payload Operations Integration Center (POIC) at the NASA Marshall Space Flight Center (MSFC) has made many payload ground system changes to enable payload developers to use these capabilities. The MSFC POIC is an ISS facility that manages the execution of on-orbit ISS payloads and payload support systems in coordination with the Mission Control Center - Houston (MCC-H) at the Johnson Space Center (JSC). The POIC ground segment provides a wide range of ground data services to support science operations including telemetry, commanding, voice, video, mission planning, and data storage and retrieval services. Under the CRS1 contract, the POIC developed its first interface with a commercial partner to enable payload developers to receive pressurized payload health and status (H&S) telemetry as well as some visiting vehicle environment data in real-time to give payload developers and POIC flight controllers insight into how the payloads were functioning on the visiting vehicle during the transit phase.

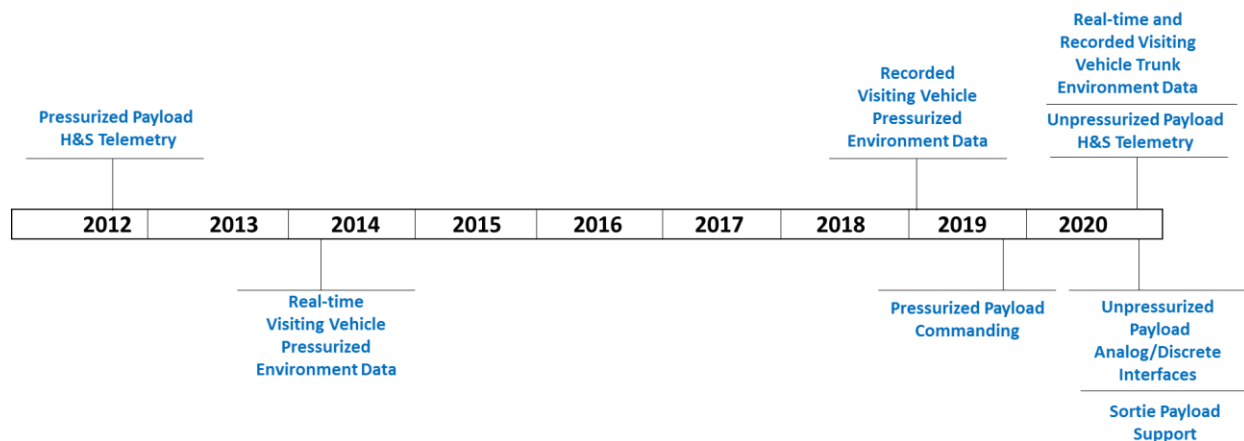
The POIC also plans to make many more ground system changes to accommodate new payload services in the future. Under the CCtCap program, the POIC is establishing a new capability with the commercial visiting vehicle providers for payload developers to retrieve recorded visiting vehicle environment data from periods in which the vehicle had a loss-of-signal (LOS) during the mission. Lastly, under the new CRS2 program, the POIC is working with the commercial visiting vehicle providers to offer payload command services to pressurized payloads as well as state monitoring and enhanced thermal environment insight capabilities for unpressurized payloads during transit.

As the POIC works with each commercial visiting vehicle provider to offer new data services to the ISS payload developer community, there are three objectives that must be kept in balance. First, payloads are designed to operate on the ISS, so the primary objective is to have the interfaces that the commercial visiting vehicles provide on board for payloads be consistent to the maximum extent feasible with the interfaces that payloads have on the ISS. This will enable scientists to use visiting vehicle data services without needing to make extensive payload hardware or software changes. The second objective is to implement payload data services on the visiting vehicles in a manner that is cost effective for each commercial partner. At the same time, the last goal is to keep POIC ground system development costs low by standardizing implementation approaches for these data services across vehicles as much as possible. Standardization will reduce the amount of custom interface software that the POIC has to develop, and reduce the costs for the POIC to support new commercial interfaces in the future.

This paper will first detail the data services that will be available to payload developers under each commercial visiting vehicle contract. Secondly, this paper will provide discussion of the most significant technical and programmatic challenges that have been faced to-date in offering these new data services to payloads related to balancing the impacts for new payload services across the payload developer community, the commercial visiting vehicle partners, and the POIC.

## **II. Overview of Payload Data Services on the Commercial Visiting Vehicles**

NASA desires for payload data capabilities on the commercial visiting vehicles have grown with each successive set of contracts. This section of this report will provide an overview of the payload data capabilities that are available today as well as information on the additional payload monitoring and commanding capabilities that NASA is working with each commercial vendor to establish in the future. See Figure II.1 on the following page for a timeline of payload data capability phasing on the commercial vehicles.



**Figure II.1 Timeline Phasing for Payload Data Capabilities on the Commercial Visiting Vehicles**

### A. Pressurized Payload H&S Telemetry Monitoring

The first payload data service that was established for powered cargo on a commercial visiting vehicle was payload H&S telemetry monitoring for pressurized payloads. This capability was first implemented in 2012 under the CRS1 contract, and it provides the ability for NASA payload developers whose experiments are designed to be integrated into EXpedite the PROcessing of Experiments for Space Station (EXPRESS) racks on board the ISS to receive payload-generated status telemetry for situational awareness. Payload H&S telemetry is also available to POIC flight controllers for monitoring.

Payload developers and POIC flight controllers receive payload H&S data whenever a payload is integrated into a visiting vehicle and powered. This means that payload developers have insight into how their experiments are operating on the launch pad prior to launch, during ascent, and while the visiting vehicle is mated to the ISS prior to the payload being transferred into a long-term operating location on the ISS. Moreover, H&S telemetry is available on the return trip as well as soon as the cargo is installed and powered inside of the vehicle until cargo is removed following the return to the Earth. Payload users typically receive H&S telemetry updates every few minutes. The intent of this service is to enable payload users to monitor payload operational status during transit to ensure quick diagnosis of any problems prior to vehicle docking or post-landing to support immediate troubleshooting response.

The H&S data that payload users receive while on the visiting vehicles is the same telemetry they receive when they are integrated into the ISS EXPRESS Racks. The EXPRESS Racks on the ISS provide structural interfaces for science experiments as well as power, data, water, cooling, and other facility necessities for operating experiments in space. When a payload is integrated into a visiting vehicle, the vehicle provides structural mounting, forced air cooling, power, and data connections to each mid-deck locker (MDL) location. The visiting vehicles support both single and double locker sized EXPRESS payloads.

To ensure that NASA payloads designed for integration into the EXPRESS racks could operate while integrated into a commercial visiting vehicle without the need for payload hardware or software changes, NASA levied several requirements on the commercial vehicle's command and data handling (C&DH) subsystem. For instance, NASA EXPRESS payloads on the ISS are designed to communicate to an ISS Rack Interface Controller (RIC) within an ISS EXPRESS Rack. The ISS Payload Ethernet Hub Bridge (PEHB) provides EXPRESS payloads with a logical Ethernet interface to the RIC. Payloads communicate to the RIC via the PEHB using the Transmission Control Protocol/Internet Protocol (TCP/IP) software protocol.

EXPRESS payloads communicate H&S telemetry messages at a rate of 1 Hz. In this set-up, the RIC is the client and the payload is the server for all RIC-to-payload communications. When a payload is integrated into a visiting vehicle, however, there is not an ISS RIC for the payload to interface with. Therefore, the visiting vehicle has to provide an Ethernet data connection to each powered MDL location and a network device that emulates ISS RIC functionality. The visiting vehicle network device must serve as the client for the TCP/IP interface with the payload and it must present itself with the same default gateway address as the RIC that the payloads are configured to communicate with while on the ISS.

Moreover, not all payloads support remote IP address reconfiguration. For this reason, the visiting vehicle's IP address space designated for the Payload Local Area Network (Payload LAN) must match the same IP address space as the one on the ISS. This enables a payload to be assigned a single IP address by NASA that will work on the visiting

vehicle and on the ISS. This eliminates the need for the ISS crew to manually change the IP addresses of the payload units that do not support remote payload reconfiguration prior to transferring them over to the ISS for long-term operations.

To support the pressurized payload H&S telemetry monitoring service for NASA EXPRESS payloads on commercial visiting vehicles, the MSFC POIC has established interfaces with the respective visiting vehicle control center. To keep the interface requirements on the commercial vehicles simple, the visiting vehicle provider simply strips all payloads' Ethernet H&S packets from their vehicle's downlink and sends them to the MSFC POIC. Once the data are received at the POIC, additional packet headers are added onto the telemetry to include Consultative Committee for Space Data Systems (CCSDS) headers and internal headers that facilitate routing of the data within the POIC ground system.

Payload users have the ability to receive their telemetry packets in real-time through a POIC tool called Ground Support Equipment (GSE) Packets. This application allows a payload user to specify a destination IP address and a port for where the user wants telemetry packets to be forwarded from the POIC. Payload users can then see current telemetry values on graphical displays. Payload users also have the ability to do a telemetry retrieval request for a specific time period through the POIC Near-Real Time (NRT) storage system.

## B. Visiting Vehicle Pressurized Environment Telemetry Monitoring

The second payload data service that was implemented for powered cargo was vehicle and payload operational environment telemetry monitoring. This capability was first introduced in 2014 during the CRS1 program and it enables payload users to retrieve a subset of telemetry generated by the visiting vehicle which characterizes the vehicle's environment. See Table II.1 below for a list of some of the vehicle telemetry parameters that are available to payload users for monitoring. Whereas this list represents the telemetry that visiting vehicles provide to payload users for monitoring during every mission, payload users do have the ability to request additional parameters if they are necessary for payload situational awareness. In this case, the ISS Program and the commercial vehicle provider will negotiate a mission-specific list of vehicle telemetry parameters.

**Table II.1 Visiting Vehicle Pressurized Environment Data Points Available to Payload Users**

<b>All Missions with Powered Cargo:</b>	
• Vehicle Cabin Temperature	• Payload Power Draw (Current and Voltage)
• Vehicle Cabin Pressure	• Vehicle Cabin Relative Humidity
<b>Additional Parameters Available for Missions with Active Environment Modules (AEMs):</b>	
• Vehicle Cabin Carbon Dioxide (CO <sub>2</sub> ) Content	• Vehicle Cabin Oxygen Content (O <sub>2</sub> )

Visiting vehicle and payload operational environment telemetry is available to payload developers in real-time for situational awareness through the POIC, and post-mission for data analysis and simulating the vehicle transfer environment in ground control experiments. Payload users can use the same tools they use for retrieving payload H&S telemetry: GSE packets and NRT List Requests. The intent of this capability is to provide payload users with situational awareness concerning the transfer environment which could provide necessary context to determine the source of off-nominal payload operating conditions. Payload users today receive vehicle-sourced telemetry from the time a payload is installed in the vehicle and powered to the time the payload is removed from the vehicle. This type of telemetry is available at a rate of one packet containing a full set of updated telemetry parameters every 10 seconds (0.1 Hz).

Visiting vehicle telemetry is downlinked by the vehicle and sent to the visiting vehicle control center. Once at the visiting vehicle control center, the telemetry of interest to payload users is extracted from the downlink, calibrated into engineering units, and then packaged into telemetry parameter records that conform to a NASA standard for ISS partner vehicles. The vehicle telemetry parameter records are then encapsulated in CCSDS packets and sent to the POIC ground segment using TCP/IP. Leveraging standard ISS formats for the commercial vehicle telemetry that is sent to NASA significantly decreases the costs to the JSC Ground Segment for supporting new commercial vehicles. However, the MSFC POIC historically has never received visiting vehicle telemetry parameters from ISS partner vehicles. For this reason, the POIC had to develop new telemetry stream processing software to process commercial vehicle environment data before this capability became operational. Now that the POIC is capable of processing the ISS standard format for visiting vehicle telemetry that is provided to NASA, the costs of supporting telemetry

interfaces with new visiting vehicle partners are low even to handle slight variations or customizations to the format standard.

Under the CCtCap program, enhancements to the original vehicle and payload operational environment telemetry monitoring capability are being implemented on the visiting vehicles. The initial CRS1 capability afforded payload users with the ability to receive real-time telemetry. Starting with the first CCtCap flight supporting powered cargo, payload users will also have the ability to receive vehicle environment parameter values from the time periods in which the visiting vehicle was LOS. With this new capability, the visiting vehicles will record environment telemetry during LOS periods on-board the vehicle, and then downlink it to the ground within a day of mating with the ISS or landing. The parameters of interest to payload users will then be extracted and sent to the POIC. The POIC storage system will then ingest the recorded telemetry packets and merge the data with the packets received in real-time. Payload users will then be able to retrieve the full mission profile of any of the vehicle telemetry parameters through doing a NRT List Request. The intent of providing payload users with recorded vehicle data from LOS periods is so that they have a full mission profile of telemetry that characterizes the payload operational environment during the ascent, on-orbit, and reentry phases for use in ground control experiments and anomaly resolution.

Overall, payload users will have a robust set of telemetry monitoring capabilities for situational awareness during the transit phase on select CRS1 and CCtCap vehicles. These passive data monitoring abilities will help scientists determine if quick troubleshooting will be necessary once the vehicle arrives to ISS or lands back on the Earth. However, in the event of a payload anomaly, there is nothing a payload user can do until after the payload is transferred out of the visiting vehicle since there is no uplink capability for payloads.

### **C. Pressurized Payload Commanding: Command Line and File Transfer Services**

In looking to the future, payload commanding during free-flight is a natural extension of the services that CRS1 and CCtCap vehicles provide. For that reason, the ISS Program included payload commanding as a new desired generic capability for the CRS2 vehicles to offer. The initial NASA guidelines for the payload command capability were that all payload commands would be routed to the vehicle from the visiting vehicle's own control center and the visiting vehicle needed to provide feedback to the visiting vehicle control center that the commands were accepted on board the vehicle. Ultimately, all three commercial companies that won CRS2 contracts proposed to provide a command capability for NASA payloads. However, the command capabilities proposed by each vendor differed fairly significantly in terms of operational concepts and interface protocols.

One significant challenge in working with the commercial vendors on concepts for payload commanding was that each interface had to be negotiated independently of the other interfaces. Due to concerns that significant interface variations across vendors would increase NASA ground system integration costs and potentially drive vehicle-specific hardware and software requirements on payload designs, the POIC worked with the ISS Research Integration Office over the last year to come up with a standard approach for payload commanding that could support ISS payload developers and the NASA use-cases for this capability in free-flight. Payload users currently have two forward-link interfaces while they are integrated into the ISS. They can use 1553 command services, or they can interact with their payloads using a variety of IP services for command line access and file transfers.

After evaluating potential use-cases for a payload command service on the visiting vehicles, the ISS Program decided to pursue implementation of a pressurized payload command capability via Ethernet and IP services instead of via a 1553 data bus and predefined payload commands in the POIC command database. IP services were selected because they offer payload developers a great amount of operational latitude to interact with their payloads, and Ethernet interfaces are less costly to develop than 1553 interfaces. However, there are a couple limitations concerning what a payload user can do with IP services. First, IP services cannot be used for any command activity that could pose an operational or safety hazard to other payloads or to the host vehicle. Secondly, a payload user must declare and seek approval for the specific protocols and services they intend to use from the NASA Safety Review Panel (SRP).

The goal for the new CRS2 pressurized payload command capability is to enable payload developers to use IP services including command line and file transfer protocols during the transit phase to make payload configuration changes and to turn payload equipment on and off. The intent is for this service to support payload developer use of Internet Control Message Protocol (ICMP), User Datagram Protocol (UDP), and Transmission Control Protocol (TCP) services. See Table II.3 on the following page for a summary of the protocols and services that the CRS2 visiting vehicles have been asked to support.

**Table II.2 Desired Protocols and Services for the CRS2 Pressurized Payload Command Capability**

Protocol	Visiting Vehicle IP Service
Internet Control Message Protocol ( <b>ICMP</b> )	<b>Ping</b>
Transmission Control Protocol ( <b>TCP</b> )	Hypertext Transfer Protocol Secure ( <b>HTTPS</b> )
	Secure Shell ( <b>SSH</b> )
User Datagram Protocol ( <b>UDP</b> )	CCSDS File Delivery Protocol ( <b>CFDP</b> )

In addition to standardizing the protocols and data interface for this payload command capability, the POIC also created a set of requirements to establish the minimum technical performance of the payload command service to ensure that the user experience would be comparable across visiting vehicles. This is particularly important because payloads will be manifested on an upcoming vehicle for transit to the ISS whenever they are ready to fly. A significant divergence across vehicles in operational performance is undesirable because it could drive the need for particular payloads to be manifested on only a specific vehicle type to meet their operational needs, thus complicating the manifesting process.

Setting the minimum acceptable performance thresholds was challenging for a couple of reasons. For one, free-flight transfer vehicles do not standardly use a lot of bandwidth for vehicle monitoring and control. For that reason, it was desirable not to request any more bandwidth for payload activities than what would be absolutely necessary to support the IP services that payload developers use most on the ISS. On the other hand, however, there was also the desire for the user's experience interacting with a payload on the visiting vehicle to be as similar as possible to the user's experience when interacting with a payload on the ISS. For context, payload users today on the ISS share 8 Mbps of bandwidth on the uplink side and 300 Mbps of bandwidth on the downlink side.

To set realistic system requirements for a transfer vehicle, the POIC did some ground testing of all IP services that are available to payload users on the ISS to characterize the bandwidth required by each service. After analyzing test data, it was determined that the visiting vehicles should not be asked to support the Remote Desktop Protocol (RDP) because it requires a significant amount of bandwidth beyond what is required for other IP services. Moreover, the most widely used IP service on the ISS is command line access via SSH. Based on ground testing data, the minimum bandwidth requirement for pressurized payload IP services was set to 56 Kbps (bi-directional). This requirement is based on an operational concept of up to two payload users each using one of the IP services listed on Table II.2 at the same time during free-flight. Since 56 Kbps is a lot of bi-directional bandwidth for a transfer vehicle, it is expected that this payload command link will only be available during short periods of time while payloads are in-transit to and from the ISS. The desire is for this service to be available for a few, five-minute command windows during each mission. See Table II.3 below for a summary of the driving technical performance requirements for the CRS2 payload command services. Additionally, if the commercial vendor has to fragment a payload forward or return packet across multiple packets for uplink to the vehicle or downlink to the visiting vehicle control center, each payload packet has to be reassembled by the visiting vehicle or visiting vehicle control center prior to transferring the data to the user. This is so that payload developers do not have to implement the ability to receive fragmented packets.

**Table II.3: CRS2 Payload Commanding Requirements**

Technical Parameter:	Minimum Threshold:
<b>Bi-directional Bandwidth</b>	56 Kbps (total, shared across all payloads)
<b>Latency</b>	One second (round-trip)
<b>Maximum Transmission Unit</b>	1500 bytes
<b>Availability during Ascent/Descent</b>	Five minutes minimum duration per command window

In order to standardize payload command line and file transfer services as the approach for visiting vehicle payload commanding, high-level NASA requirements were revised and contract change paperwork was initiated with the CRS2 vendors. Currently, NASA is in the process of reviewing these new service requirements with each partner and evaluating whether or not it makes sense to go forward with these capabilities on each vehicle.



#### D. Unpressurized Payload H&S and Visiting Vehicle Trunk Environment Telemetry Monitoring

A second set of payload data services that are coming online with the start of the CRS2 program are unpressurized payload H&S telemetry monitoring and visiting vehicle trunk environment telemetry monitoring. Under the CRS2 program, visiting vehicles that support unpressurized cargo will be providing power for payloads to be active while in transit to and from the ISS. To support unpressurized payload situational awareness, the visiting vehicles will be downlinking the payload H&S telemetry generated by payloads designed to be integrated into the Express Logistics Carrier (ELC) on the ISS and providing the payload packets to the POIC for distribution to the payload users. Moreover, the visiting vehicles will be providing additional vehicle environment telemetry for situational awareness concerning the unpressurized trunk environment. The list of new telemetry parameters that will be available to payload users for monitoring is shown in Table II.4 below.

**Table II.4: Visiting Vehicle Unpressurized Trunk Environment Data Points for Payload Users**

<b>Additional Parameters Available for Missions with Active Unpressurized Payloads:</b>	
<ul style="list-style-type: none"><li>• Temperatures of the Vehicle Structure Exposed to Cargo</li></ul>	<ul style="list-style-type: none"><li>• Cargo Heater Power Consumption (Voltage and Current)</li></ul>

To ensure that the visiting vehicle interfaces for unpressurized powered cargo can support NASA ELC payloads without requiring extensive payload hardware or software redesign, the visiting vehicle's C&DH system is required to provide MIL-STD-1553 or Ethernet data connections to each powered trunk location and to transfer payload H&S telemetry for downlink via 1553 or Ethernet protocols. The standard interface on the ISS that ELC payloads use to downlink H&S telemetry is 1553, but many payload users do have the ability to downlink H&S telemetry via Ethernet as well.

The visiting vehicles will provide payload users with updated H&S packets whenever an unpressurized payload is integrated into the visiting vehicle and powered. Unpressurized payloads generate H&S packets at a rate of 1 Hz. While the vehicle is on the pad prior to launch, updated telemetry will be provided at least once per day. During free-flight when the vehicle has launched but not yet mated with the ISS, H&S telemetry will be provided at least once per minute. Lastly, on the return trip, H&S telemetry will be provided again at a rate of at least once per minute after the vehicle has departed station but before it has conducted reentry operations.

Vehicle trunk environment telemetry will also be available to payload users from the time unpressurized cargo is loaded into the vehicle and powered until the cargo is removed from the vehicle following arrival at the ISS or return to the Earth. Updated cargo heater power consumption and vehicle trunk temperature parameters will be available once every ten seconds (0.1 Hz) prior to launch, and once per second (1 Hz) all other times. The CRS2 visiting vehicles will also record unpressurized environment parameters during LOS periods and provide the data to the POIC for distribution to payload users within one day of the vehicle arriving to station or landing back on the Earth. This way, payload users will have access to the full mission profile of vehicle unpressurized environment data post-mission to assist in characterizing the expected environment for ground controls, or investigating on-orbit payload anomalies.

#### E. Analog and Discrete Line Interfaces for Unpressurized Payloads

The third set of interfaces that the NASA Research Integration Office desires for CRS2 vehicles to provide for unpressurized powered payloads are analog and discrete lines. For this capability, the visiting vehicle would need to provide analog and discrete interfaces to each trunk payload location. There are two payload operational use-cases for these interfaces. First, the analog interfaces could be used for temperature monitoring for payloads that have Resistance Temperature Detectors (RTDs). For this to work, the vehicle would have to provide a constant current to drive and monitor the RTDs, and then convert the analog signals coming back from the RTDs into digital values for downlink. This would provide payload users with temperatures at the payload sites themselves, which could provide more accurate insight into the payload thermal conditions than the vehicle temperature environment data sensors. Second, this interface could be used for payloads to receive analog or discrete inputs from the visiting vehicle. Payload developers who have designed experiments to do such things as change operational configuration based on the receipt of a specific analog or discrete signal could use this capability to interact with their payloads during transit to and from the ISS. Currently, NASA is in the process of working with the CRS2 partners to see if these analog and discrete services could be provided to unpressurized payloads while they are integrated into the visiting vehicles.

## **F. Visiting Vehicle Support for Long-duration Payload Operations (Sorties)**

The last new payload data capability in-work for the CRS2 program is sortie payload support. For the purposes of this paper, a sortie payload is defined as an ISS payload that is physically located on the visiting vehicle for science operations while the vehicle is attached to the ISS. This would include payloads that are taken up to the ISS on a visiting vehicle and left on the visiting vehicle (they never cross the hatch over to the ISS), and operational payloads that are relocated from the ISS onto the visiting vehicle. In this concept for CRS2 support for long duration payload operations, the ISS Joint Station LAN (JSL) and Payload LAN would be extended over into the visiting vehicle so that EXPRESS and Ethernet payloads could access standard telemetry and command services provided by the ISS onboard systems. This capability would provide NASA with additional payload support capacity as well as a significant amount of flexibility in locating payloads in the operational environment that is best suited for their needs.

## **III. Technical and Programmatic Challenges Faced While Negotiating Implementations for Payload Data Services**

As the POIC has been working with the ISS Program and the commercial visiting vehicle providers to set the goals, expectations, and implementation plans for new payload data services, there have been many technical and programmatic challenges that have had to be overcome. To start, on the technical side, working an end-to-end concept with a commercial partner for a new payload service requires a significant amount of cross-discipline integration. At NASA, there are many different functional organizations that each have subject matter expertise in some piece that is necessary for a feasible end-to-end concept. For instance, there are NASA subject matter experts across JSC and MSFC that know such things as the avionics and software design of each visiting vehicle; EXPRESS and ELC payload hardware and software design; unpressurized cargo integration processes; NASA test equipment and verification requirements; information technology (IT) security requirements; ISS SRP processes; commercial vehicle contract change processes; NASA ground-based networks; payload ground system design; NASA interfaces to remote payload users; operational procedure development and execution for real-time operations; and payload operational concepts for telemetry and commanding on the ISS. All of these disciplines on the NASA side have had to work together with the various reciprocal disciplines on the commercial vendor side in order to move forward working these capabilities. When working in an environment that requires this much integration across organizations, it can be difficult to clearly define what each organization is responsible for doing to ensure that there are no gaps, and to communicate concerns and problems to all affected parties. Likewise, it can be difficult to identify all stakeholders that need to be included in reviewing technical designs and driving the operational concepts to ensure the feasibility of the end-to-end system.

For example, to generate a set of new requirements for payload analog and discrete interfaces, the POIC worked with the Research Integration Office and the ELC payload design experts. When it came time for the ISS program to review and approve the requirements, however, the requirements development team became aware that there was also an Unpressurized Cargo Integration team that had a significant stake in the requirements. That team should have been significantly involved in determining the scope of the analog and discrete services needed to support unpressurized cargo operations instead of having been categorized as just a reviewer of the requirements. This led to a lot of rework that could have been avoided if all of the stakeholders that needed to be involved in driving what the requirements needed to be had been properly identified and included in the development effort from the beginning.

Other challenging technical aspects of working payload data service implementations with the commercial partners have included the level of integration required between the POIC and each visiting vehicle control center, and the evolutionary nature of these services. The POIC provides many ground system services to support remote payload users. For this reason, there are no direct interfaces between the visiting vehicle control centers and the ISS payload developer community. The visiting vehicle control centers interface with the POIC. Therefore, there are a lot of negotiations that have to take place between the POIC ground segment and the commercial vehicle ground segment related to network connectivity and ground system design. These negotiations have to take place bi-laterally, meaning between the POIC and each commercial provider, and payload data services are being established with each partner on a different timeline as NASA program level requirements are established. This makes it difficult for the POIC to determine the most efficient network connectivity and ground segment design approaches to implement since the full set of requirements for all external commercial partner interfaces will not be truly understood until all ground segment interfaces are negotiated and documented.

For instance, when the POIC first developed a telemetry stream processor for visiting vehicle environment data, the processor was set up to only support data processing for one stream of telemetry at a time. The POIC later had to make changes to the processor to enable processing for multiple simultaneous streams of data so that more than one vehicle activity could be supported at the same time (e.g., two mission activities or one flight activity and a separate test activity). This was a labor cost that could have been avoided if the POIC had known at the time the interface was



set-up that other vehicles in the future would also be providing vehicle telemetry for payload users. To help mitigate the impacts of designing POIC ground systems based on a limited set of known requirements, the POIC has spent a lot of time working with the ISS Research Integration Office to get a better understanding of how they envision payload needs for data services on the visiting vehicles growing over time. This allows the POIC to take future interfaces into consideration when designing interfaces for use now to make sure nothing is implemented that will make future enhancements or extensions difficult.

One programmatic challenge with working new payload data services on the commercial visiting vehicles has been getting consensus within the ISS Program on the philosophy for the services. On one hand, NASA is working diligently to foster commercialization of Low-Earth Orbit (LEO). One way to help that effort, is to support commercial vendors in designing unique services for payload customers and in selecting specific implementations for services that are commercially cost effective. A potential business case for commercial transfer vehicles is supporting satellite deployments and research payloads. But, the current need with respect to the ISS program is for the ISS transfer vehicles to support payloads that have been designed for ISS structural, electrical, and data interfaces. If you add interface requirements that restrict implementation for payload data services to what payloads have on the ISS in order to not impact payload design requirements, the trade space of what the visiting vehicles can offer to payloads is very limited. Ultimately, the ISS Program decided to pursue the development of payload data services on the visiting vehicles that ISS payload users can take advantage of without needing to redesign their experiment hardware or software. Another question that has been discussed is how to balance the desire to support the commercial vendors in making ground segment interface implementation decisions that are cost efficient for the partner and the competing desire that the POIC has to limit NASA-side ground segment interface development costs through standardizing approaches across partners. In this case, the decision of whether to accept interface deviations or enforce POIC standards is made on a case-by-case basis depending on the magnitude of the impact on each side of the interface.

#### **IV. Conclusion**

As the POIC works with the ISS Program and each commercial provider to bring NASA's desires for enhanced payload data services on the CCtCap and CRS2 vehicles into reality, it is necessary to strike a proper balance between enforcing the implementation of standard interfaces across commercial partners and supporting vendor-unique implementations that are economical. If these objectives can be balanced, payload users stand to have a robust set of payload telemetry and command capabilities on the upcoming commercial vehicles in design now. Payload H&S and visiting vehicle telemetry monitoring provide payload users with the situational awareness they need to be cognizant of their payloads' operational state prior to arrival to ISS or landing on the Earth so that actions can be taken immediately to address anomalies that occurred during transit. Moreover, payload commanding via IP services is a natural enhancement to payload monitor-only capabilities that will enable a payload developer to take action to save a payload in the event of an operational anomaly. The new analog and discrete interfaces for unpressurized payloads will provide unpressurized cargo with enhanced insight into the thermal conditions at the payload site and lastly, visiting vehicle support for sortie payload operations post-mating with the ISS will provide NASA with increased ISS capability for hosting science. Moving forward, the POIC will strive to implement new payload data services with each commercial visiting vehicle partner in a manner that is both cost effective for all parties and meaningful in supporting the operational concepts that payload developers have today.

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